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Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions

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[1] Using projections from two coupled climate models (HadCM3C and HadGEM2-AO), we consider the effect on 21st century sea-level rise (SLR) of mitigation policies relative to a scenario of business-as-usual (BAU). Around a third of the global-mean SLR over the century is avoided by a mitigation scenario under which global-mean near surface air temperature stabilises close to the Copenhagen Accord limit of a 2°C increase. Under BAU (a variant of the A1B scenario) the model-averaged projected SLR for 2090–2099 relative to 1980–1999 is 0.29 m–0.51 m (5%–95% uncertainties from treatment of land-based ice melt); under mitigation (E1 scenario) it is 0.17 m–0.34 m. This reduction is primarily from reduced thermal expansion. The spatial patterns of regional SLR are fairly dissimilar between the models, but are qualitatively similar across scenarios for a particular model. An impacts model suggests that by the end of the 21st century and without upgrade in defences around 55% of the 84 million additional people flooded per year globally under BAU (from SLR alone) could be avoided under such mitigation. The above projections of SLR follow the methodology of the IPCC Fourth Assessment. We have, however, also conducted a sensitivity study of SLR and its impacts where the possibility of accelerated ice sheet dynamics is accounted for. **Citation:** Pardaens, A. K., J. A. Lowe, S. Brown, R. J. Nicholls, and D. de Gusmão (2011), Sea-level rise and impacts projections under a future scenario with large greenhouse gas emission reductions, *Geophys. Res. Lett.*, *38*, L12604, doi:10.1029/2011GL047678.

1. Introduction

[2] A stated aim of the Copenhagen Accord is to keep increases in global mean near surface air temperature below 2°C (http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf). This would require stringent mitigation policies to reduce greenhouse gas emissions. Under global warming sea-level rise (SLR) will probably cause sizeable impacts on society. Mitigation will be less effective in stabilising sea level than in stabilising surface air temperature as sea level approaches a new equilibrium on a much longer, millennial, timescale [e.g., *Meehl et al.*, 2007].

[3] For business-as-usual (BAU) future scenarios, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report ('AR4') gave a projected range of global-mean SLR over the 21st century (1980–1999 to 2090–2099) of 0.18–0.59 m (across *Meehl et al.*'s [2007] range of future scenarios). Illustrative examples of how ice sheet dynamics might scale with global warming give an addition of up to 0.17 m. For the SRES A1B scenario, AR4 gave a projected range of 0.21–0.48 m. Thermal expansion of the warming ocean waters, together with melting of glaciers and small ice caps and net melt of the large Greenland and Antarctic ice sheets, constitute the major components of global-mean SLR. Local sea level generally differs from the global-mean due to an interplay between ocean dynamics and density variations in the subsurface ocean. Changes in these under global warming can give local SLR that differs notably from the global-mean [e.g., *Meehl et al.*, 2007].

[4] Mitigation scenarios were not included in the projections given by AR4. There have, however, been some studies of the influence of stringent or idealised mitigation scenarios on thermal expansion [e.g., *Wigley*, 1995; *Solomon et al.*, 2009; *Washington et al.*, 2009], although only limited projections using a General Circulation Model (GCM) [*Washington et al.*, 2009]. In this study we provide mitigation scenario projections for two additional GCMs. We also analyse a number of aspects of SLR under mitigation relative to BAU which have not been included in previous studies. These include projections of the land-based ice melt component of SLR, together with a sensitivity study where accelerated ice dynamics are assumed, and a consideration of regional variations in sea-level rise. We also apply an impacts model, to estimate the avoided damage in terms of the annual additional number of people flooded.

2. Data and Methods

[5] The projections we use are part of a wider multi-model climate experiment from the European Commission ENSEMBLES project [*Lowe et al.*, 2009; *Johns et al.*, 2011]. For BAU we refer to two different A1B scenarios: primarily focusing on the A1B (IMAGE) scenario, but also giving global-mean SLR under SRES A1B for comparison with well documented AR4 sea level projections available for this scenario. Under A1B(IMAGE), the CO_2 equivalent concentration (CO_2-e) increases to around 1050 ppmv by 2100; for SRES A1B the CO_2-e increases to around 835 ppmv [*Meehl et al.*, 2007]. Our mitigation scenario E1 starts from the A1B(IMAGE) baseline (there is no corresponding SRES E1 scenario). Under E1, the CO_2-e concentration starts to diverge from that of A1B(IMAGE) around 2010, peaks around 530 ppmv in 2045 and subsequently decreases to stabilise around 450 ppmv during the 22nd century.

[6] This study uses two Met Office coupled ocean-atmosphere climate models: HadCM3C and HadGEM2-AO.

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For both models, atmospheric CO_2 concentrations are specified as inputs to the projections. HadCM3C and HadGEM2-AO ocean component models have resolutions of 1.25° and 1° respectively, decreasing to $\frac{1}{3}$° latitudinally at the equator for HadGEM2-AO. Global-mean thermal expansion of the ocean water column is calculated from the ocean temperature-related change in density. The land-based ice melt component of SLR is calculated following the AR4 approach where a range of possible contributions (Sea Level Equivalent 'SLE') are derived which are consistent with the hierarchy of current modeling capability [*Meehl et al.*, 2007]. AR4 noted, however, a lack of scientific understanding or modelling capability of potential future dynamical acceleration of ice sheets and for this reason they did not include this effect in their SLR projections. Since AR4, *Pfeffer et al.* [2008] have proposed, on the basis of physically tenable accelerated conditions, that a SLR to 2100 of 0.8 m might form a "most likely" starting point for refining scenarios to include these processes (we take this to be a BAU scenario). We construct BAU and mitigation scenarios for a sensitivity study of SLR and its impacts under potential glaciologically accelerated conditions ("AccID" scenarios): the total land-based ice melt contribution under BAU is adjusted to be consistent with the above scenario of *Pfeffer et al.* [2008] while the rates of contribution from accelerated ice sheet dynamics under BAU and mitigation are obtained by a scaling with global-mean near-surface air temperature, based on the illustrative scaling approach used by AR4. Recent "semi-empirical" projections of SLR also tend to be notably larger that those given by AR4. *Lowe and Gregory* [2010], however, note the underlying reasons for this and suggest that there is little evidence to support the inherent assumptions.

[7] To estimate impacts on coastal populations of the SLR projections, the Dynamic Interactive Vulnerability Assessment (DIVA) model was used. DIVA is an integrated socio-biophysical-economic model of coastal systems and impacts from changes in sea-level, driven by socio-economic and climate change [*Vafeidis et al.*, 2008; *Hinkel and Klein*, 2009]. See auxiliary material for further details of models and methods.[1]

3. Results

[8] Under the SRES A1B scenario, HadCM3C and HadGEM2-AO give increases in global-mean surface air temperature (at 1.5 m height) relative to pre-industrial values of 3.7°C and 3.5°C respectively by the end of the 21st century (2080–2099 relative to 1861–1890). Under A1B(IMAGE), projections by these models give somewhat larger increases in global-mean surface air temperature of about 4°C: 4.4°C for HadCM3C; 4.0°C for HadGEM2-AO. Under the mitigation E1 scenario, however, surface air temperature begins to stabilise towards the middle of the century and by the end of the century the temperature increases are approximately half those under BAU, being 2.2°C and 2.0°C for HadCM3C and HadGEM2-AO respectively.

[9] The global-mean SLR projection time series for HadCM3C and HadGEM2-AO are very similar to each other (Figures 1a and 1b). For comparison with AR4 results, the range of 21st century global-mean SLR under the SRES A1B scenario (not shown), averaged for HadCM3C and HadGEM2-AO, is 0.23 m to 0.43 m with a median of 0.33 m (range is 5% to 95% from uncertainties in land-based ice melt; changes for 2090–2099 period relative to 1980–1999). This range is within, but covering a substantial fraction of, the AR4 range for this scenario of 0.21 m to 0.48 m which additionally includes uncertainties arising from the model ensemble spread in projected thermal expansion and surface air temperature changes. Under A1B(IMAGE), which forms the baseline scenario for E1, SLR averaged for HadCM3C and HadGEM2-AO is somewhat higher with a range of 0.29 m to 0.51 m and a median rise of 0.39 m by the 2090s. Under mitigation, about 0.13 m of this median rise is avoided, reducing the median rise to 0.26 m and giving a projected range of 0.17 m to 0.34 m. Projections of SLR under the sensitivity study scenarios with assumed glaciologically accelerated conditions (AccID scenarios, Figure 1c) give a SLR that is almost doubled, with 0.72 m for BAU A1B(IMAGE)_AccID and 0.47 under the mitigation E1_AccID scenario.

[10] There is little difference over the first few decades between SLR under the baseline BAU scenario of A1B (IMAGE), which we now focus on, and under mitigation (Figure 1). Under non-glaciologically accelerated conditions, which we consider first, thermal expansion and land-based ice melt each contribute about half of the median rise for the initial decades. SLR then accelerates under BAU and slows under mitigation with the acceleration under BAU dominated (for the median) by increases in the rate of thermal expansion. Under mitigation (E1) the contributions from thermal expansion and from the median land-based ice melt remain ≈50% each. The avoided SLR is primarily due to a reduction in thermal expansion: the net land-based ice melt component is more similar under BAU and mitigation. Under the AccID scenarios, however, land-based ice melt dominates SLR, contributing about 2–2.5 times as much of the SLR as thermal expansion over the century. For these scenarios the reduction in land-based ice melt forms a larger part of avoided SLR under mitigation.

[11] The difference in timescales over which surface air temperature and thermal expansion approach stabilisation is illustrated by the evolving relationship between them (Figure 2). This relationship is near linear in the initial decades as radiative forcing is increased and the near surface ocean dominates thermal expansion. As the century progresses, however, heat added to the upper ocean is slowly mixed to the deeper ocean. For BAU this process gives some deviation from linearity at the higher surface air temperatures (Figure 2) and under mitigation it gives a sharp change from linearity as surface air temperatures stabilise while thermal expansion continues to rise. A similar analysis for the land-based ice melt SLE under non-glaciologically accelerated conditions and surface air temperature change (not shown) gives similar forms of the relationship but shows a near linear relationship even at the higher temperatures reached under BAU. Under mitigation this relationship is again strongly non-linear, as for thermal expansion, because although the surface air temperature stabilises, its higher values maintain an increased net rate of ice melt (and so contribution to SLE).

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047678.

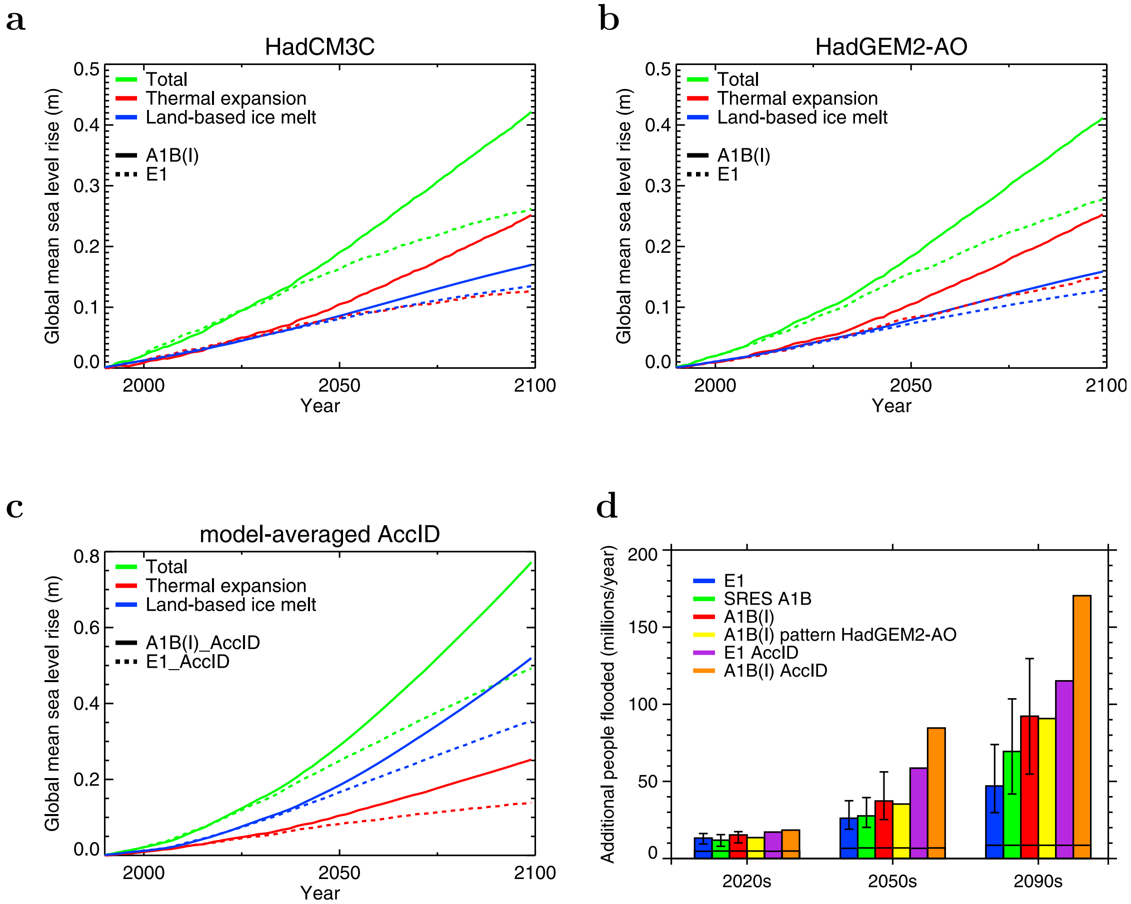

Figure 1. Global-mean projections of SLR over the 21st century for the A1B(IMAGE) and E1 scenarios, together with thermal expansion and land-based ice melt components. Median projections relative to 1980–1999 are shown for the (a) HadCM3C and (b) HadGEM2-AO models and (c) for model-averaged AccID scenario projections with larger contributions from potential accelerated ice sheet dynamics. Note different scale for Figure 1c. (d) Additional people flooded globally per year (relative to 1980–1999) under these scenarios shown for three sample decades. Impact estimates are from DIVA, driven by global mean SLR averaged for HadGEM2-AO and HadCM3C and without upgrade in defences. Impact also estimated using regional pattern of SLR (with median global-mean) from HadGEM2-AO underA1B(IMAGE). Coloured bars give estimates under median SLR; vertical lines show range for 5% to 95% range of global-mean SLR. Outlined boxes give the coastal flooding impact without SLR, so forming the baseline for climate change effects.

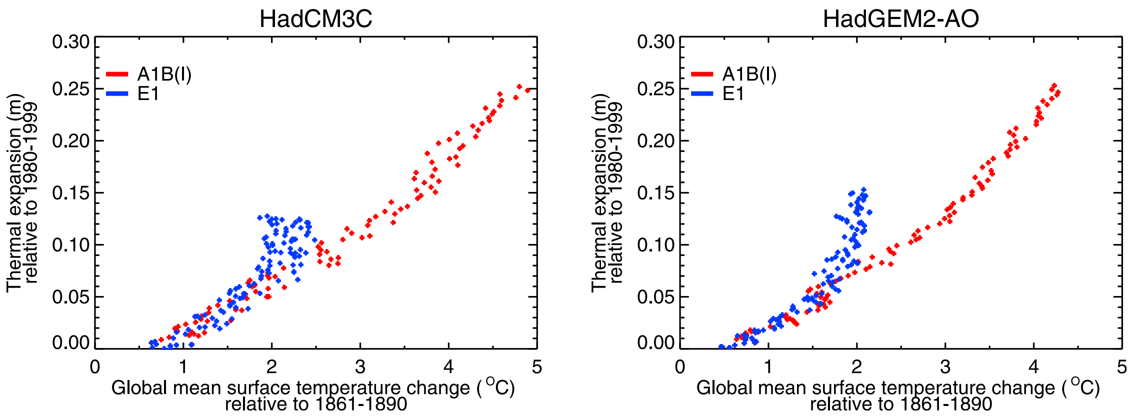

Figure 2. Relationship between 21st century thermal expansion and global-mean near surface air temperature change for the HadCM3C and HadGEM2-AO models under the A1B(IMAGE) and E1 scenarios. Each dot represents an annual mean over the 1990 to 2100 period.

[12] The similarity of the land-based ice melt SLE under the non-glaciologically accelerated BAU and mitigation scenarios is because notable compensatory changes affect the subcomponents of this. The rate of contribution to SLR from projected glacier and small ice cap melt will tend to increase with surface air temperature but will tend to decrease as the volumes and surface areas of these ice masses reduce. The net result is that these compensatory effects combine to give more similar rates of contribution to median SLR both between BAU and mitigation scenarios and over time. For the larger ice sheets, the projected higher net melt of the Greenland ice sheet under BAU is largely compensated for by a greater projected fall in SLE arising from Antarctic ice sheet changes as increased snowfall sequesters freshwater from the ocean. Over recent years, however, both ice sheets have been found to be contributing positively to SLR [e.g., *Rignot et al.*, 2011]. An ongoing rate of contribution to SLR (0.32 ± 0.35 mm yr^{-1}), equal to that inferred to be due to ice sheet dynamical acceleration for recent years (1993–2003) is included in the standard AR4 SLR projections. Some part of estimated recent increases may, however, be related to non-anthropogenically-forced variability. For future projections with glaciologically accelerated conditions the land-based ice melt is less dominated by the compensatory effects noted above.

[13] While global-mean sea level projections for HadCM3C and HadGEM2-AO are very similar, there are notable differences between their regional sea level projections despite a number of common features (e.g., both have negative changes relative to the global-mean in the Southern Ocean, see Figure S3 in auxiliary material). For each model separately, however, regional patterns of change are similar across the BAU and mitigation scenarios: spatial correlations between A1B(IMAGE) and E1 changes are 0.79 for HadCM3C and 0.76 for HadGEM2-AO), albeit with greater magnitude of the deviations (spatial RMS) under BAU.

[14] The SLR results above are further supported by auxiliary material. The potential impact of SLR, in terms of the additional people flooded if defences are not upgraded with time from 1995 levels, is estimated using model-averaged global-mean projections of SLR to drive the DIVA impacts model (Figure 1d). We first consider non-glaciologically accelerated conditions. The numbers of additional people flooded globally per year under BAU and under mitigation increasingly diverge after mid-century (as SLR diverges). By the 2090s, between 46 million and 121 million additional people are flooded per year from SLR alone under A1B(IMAGE) (ranges obtained using 5% and 95% SLR uncertainty limits and stated relative to the baseline without projected SLR), with 84 million additional people per year flooded for the median SLR (61 million for SRES A1B). For an illustrative example of the effects of regional variations in SLR on impacts, DIVA is also driven with the SLR pattern from HadGEM2-AO under the same A1B (IMAGE) scenario, using its median global-mean SLR. This gives virtually the same global-mean number of additional people flooded (82 million per year by the 2090s) as when using the global-mean SLR. Under mitigation the impact is substantially reduced with between 21 and 65 million additional people flooded per year and a median of 38 million per year. For the sensitivity study AccID scenarios with accelerated ice sheet dynamics, a substantially greater number of additional people are projected to be flooded per year from SLR alone: 162 million under BAU and 107 million under mitigation.

4. Summary and Discussion

[15] This study has explored the potential for large reductions in greenhouse gas emissions to reduce future SLR and its impacts over the 21st century. Projections of global-mean SLR by two coupled climate models, HadCM3C and HadGEM2-AO, are similar for a given scenario. The model-averaged 21st century SLR (1980–1999 to 2090–2099) under the baseline BAU A1B(IMAGE) scenario for non-glaciologically accelerated conditions is 0.39 m for the median projection. Under stringent mitigation, where the global-mean temperature increases are near-stabilised close to the Copenhagen Accord limit of 2°C by the end of the 21st century (relative to 1861–1890), around a third of this SLR can be avoided.

[16] These results should be considered in the context of wider modeling uncertainties. The projected surface air temperature increases for HadCM3C and HadGEM2-AO under BAU SRES A1B are towards the higher end of the AR4 range [*Meehl et al.*, 2007, Figure 10.5] although global-mean SLR also depends on the rate of ocean heat uptake and the expansion efficiency of heat. The model-averaged range of SLR under SRES A1B and for non-glaciologically accelerated conditions (5% to 95% range of 0.23 m to 0.43 m) is within, but a substantial fraction of, the AR4 range for this scenario. Under A1B(IMAGE) the model-averaged range is 0.29 m to 0.51 m with a median of 0.39 m, while under E1 the range is 0.17 m to 0.34 m with a median of 0.26 m. Uncertainties in the estimates of land-based ice melt under BAU and mitigation scenarios are correlated. This means that uncertainty in the avoided SLR is lower than uncertainty in SLR under a particular scenario. Under sensitivity study scenarios with assumed accelerated ice sheet dynamics, where land-based ice melt under BAU is adjusted to be consistent with the "most likely" scenario of *Pfeffer et al.* [2008], SLR is 0.72 m under A1B(IMAGE)_AccID and 0.42 m under E1_AccID, dominated by land-based ice melt.

[17] *Washington et al.*'s [2009] coupled climate model (CCSM3) study of thermal expansion under BAU and mitigation gives very similar 21st century increases in this component (22 cm under BAU and 14 cm under mitigation) to our model projections. Their scenarios bear similarities to ours: under their mitigation scenario CO_2 reaches 450 ppm by 2100 without an overshoot while under E1 CO_2 reaches ≈420 ppm at 2100, decreasing from a peak of ≈440 ppm; their BAU scenario reaches approximately 740 ppm by 2100 while A1B(IMAGE) reaches ≈780 ppm and SRES A1B reaches ≈700 ppm; their and our projections are under multi-gas scenarios which may give additional forcing differences. The global-mean surface air temperature increases in their projections, however, are less than for our projections over the same time period (by more than a degree for their BAU scenario relative to A1B(IMAGE) and by about 0.4°C for their mitigation scenario in comparison to E1). This suggests that heat uptake efficiency and/or expansion efficiency of heat in *Washington et al.*'s [2009] model may be greater.

[18] Regional variations in SLR are fairly dissimilar for HadCM3C and HadGEM2-AO although there are some common features. This is consistent with previous model intercomparison studies [*Gregory et al.*, 2001; *Meehl et al.*, 2007; *Pardaens et al.*, 2010] which suggest factors which may influence some of these differences. Patterns of SLR for each model separately, however, are qualitatively similar between the BAU and mitigation scenarios (as found for alternative BAU scenarios in AR4). We suggest that this may indicate similar dominant patterns of change in subsurface ocean temperature and salinity and in ocean circulation take place. In addition, for each model, the magnitude of regional sea level variations tends to increase for scenarios with increasing global-mean sea level. This means that where BAU SLR is locally largest, the benefit of mitigation (in terms of amount of SLR avoided) may be greater than for the global-mean. Conversely, mitigation may have less benefit in regions where BAU SLR is smaller than the global-mean.

[19] The relative similarity of SLR under BAU and mitigation (without glaciologically accelerated dynamics) until the 2050s suggests that, for this period, planning and adaptation measures could be less scenario dependent. Later the scenarios increasingly diverge and by the 2090s and without adaptation 84 million additional people per year are flooded from SLR alone under the BAU A1B(IMAGE) median SLR but this reduces by about 55% under the E1 mitigation scenario. This illustrates impacts for the case of median SLR but it is important for policy makers and planners to consider the full potential range. Under the sensitivity study AccID scenarios, with larger contributions from accelerated ice sheet dynamics, SLR and potential impacts are much greater. About twice the number of additional people are flooded per year from SLR alone under BAU when land-based ice melt is increased to be consistent with *Pfeffer et al.* [2008].

[20] Analysing impacts with the inclusion of regional variations in SLR gives similar numbers of additional people flooded per year as obtained using the global-mean SLR (for a case study). We would expect this to be the case when the regions of high population that are particularly vulnerable (primarily the Asian deltas) do not display strong anomalies from the global-mean SLR. For some coastal regions, however, regional variations in SLR will be important for projected impacts. The different patterns of sea level rise projected by different models will give some uncertainty in this (S. Brown , R. Nicholls, J. Lowe, and J. Hinkel, Spatial variations in sea level rise and global impacts: An application of DIVA, manuscript in preparation, 2011).

[21] Even under the E1 stringent mitigation scenario and non-glaciologically accelerated conditions the number of additional people potentially at risk of flooding from projected SLR alone by the 2090s is tens of millions per year and is around five times greater than that under projected coastal population changes alone. Adaptation will thus still be required even with mitigation, consistent with the conclusions of *Nicholls et al.* [2007].

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